Advances in Modeling and Simulation Capabilities for Predicting Store Trajectories – Past Success and Future Challenges

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ABSTRACT

Any time a new aircraft is introduced into service, or an old aircraft undergoes substantial modifications or needs to be certified to carry and employ new stores, the store separation engineer is faced with a decision about how much effort will be required to provide an airworthiness certification for the aircraft and stores. Generally, there are three approaches that have been used: Wind Tunnel Testing, Computational Fluid Dynamics (CFD) analyses and Flight Testing. During the past twenty years there have been considerable advances in all three areas. In particular, the US Navy has developed an integrated approach that uses the best features of the three approaches to improve the process.

This approach has led to a continuing improvement[1,2,3,4] in the Navy's Modeling & Simulation (M&S) capability for store separation. In this paper M&S refers to the combination of store freestream and grid data (obtained either from a wind tunnel or via CFD) in a six degree of freedom program to compute store trajectories. This paper presents the latest result in this process.

1.0 NOMENCLATURE

BL: Aircraft Buttline, positive outboard, in.
C_l: Rolling moment coefficient, positive rt wing down
C_m: Pitching moment coefficient, positive up
C_N: Normal Force coefficient, positive up
C_n: Yawing moment coefficient, positive nose right
C_p: Pressure Coefficient
C_Y: Side force coefficient, right
FS: Aircraft Fuselage Station, positive aft, in.
M: Mach number
P: Store roll rate, positive rt wing down
Q: Store pitch rate, positive nose up
R: Store yaw rate, positive nose right
X/C: longitudinal displacement divided by wing chord
Z: Store C.G. location, positive down, ft.
α: Angle of attack, deg.
ϕ: PHI Store roll angle, positive rt wing down, deg.

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ψ: PSI Store yaw angle, positive nose right, deg.
θ: THE Store pitch angle, positive nose up, deg.
WL: Aircraft Waterline, positive up, in.

Note: all wind tunnel and flight test data shown are right wing justified

## 2.0 WIND TUNNEL TESTING

2.1 Carriage Loads

There have been three developments in wind tunnel testing that have improved the process. The first was the determination that store loads measured with the store on the carriage pylon could vary considerably from those measured from an aft mounted sting. Comparison with flight test data demonstrated that pylon measured loads gave better trajectory predictions[5], particularly at transonic Mach numbers.

### 2.2 Store Attitude Effects for Grid Testing

The second improvement in wind tunnel testing occurred as a direct result of the close integration between the wind tunnel and flight test community. Flight test data had demonstrated that store attitude effects were critical to getting a good trajectory match with flight test results. Flight test data were then used to determine which of these effects were dominant.

Originally[5], for every data point (i.e. Mach number, aircraft angle of attack) three values of x and y (coupled), three of θ and ϕ, and five of ψ were taken for every z position (18 grids). At the end of the flight test program, it was discovered that if only one value of x, y and ϕ and two values of θ and ψ had been taken (5 grids), the results would have been similar, while reducing the size of the wind tunnel test program by more than a factor of 3. As may be seen in Figure 1, the prediction using a grid of 5 variables was just as good as that using the original 18. However, using only one grid variable, the prediction departs from the test data when the attitudes exceed 10 degrees in pitch and yaw.
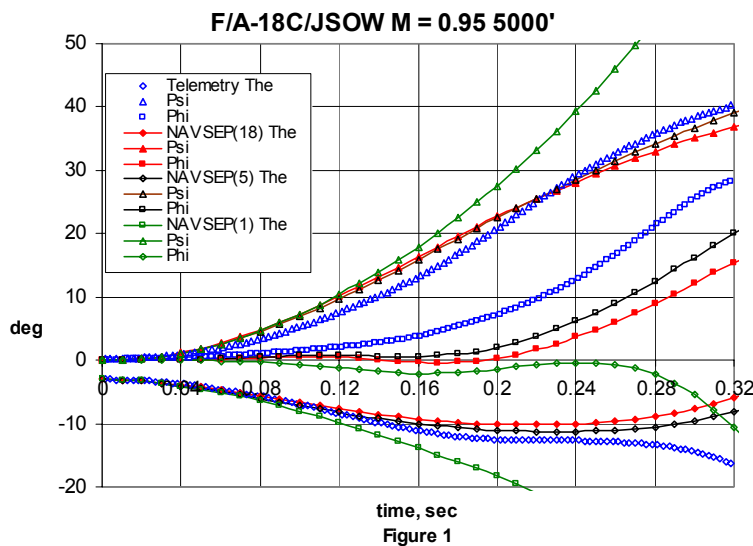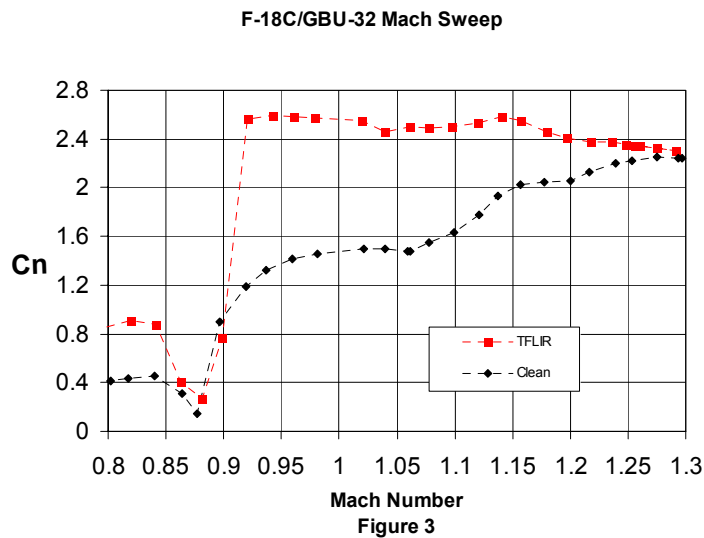

Figure 1

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Recently, the GBU-31, GBU-32 and GBU-38 (GBU refers to Glide Bomb Unit) stores certification programs were successfully completed using one value of x, y, and roll angle, and three values of yaw and pitch angles (7 grids). As may be seen in Figure 2, excellent correlation was achieved between the predictions and test data.

F/A-18C/GBU-31 M = 0.96 6382' 43° dive

Figure 2
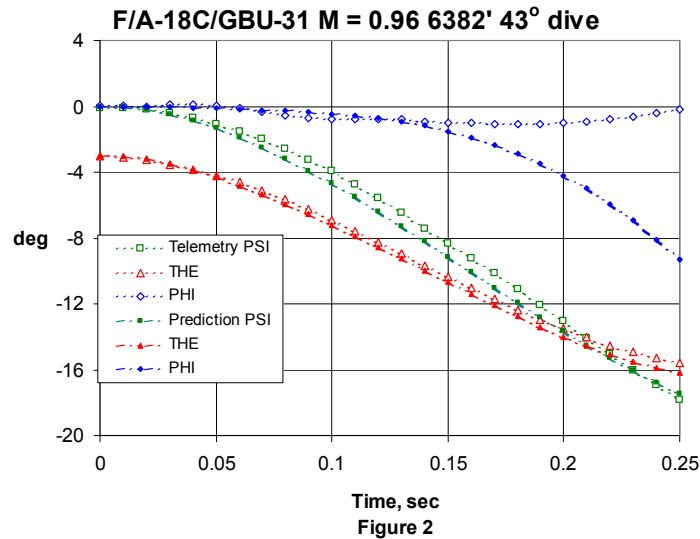
2.3 Mach Sweep effects

A third change in the method of store separation testing was the development of the Mach sweep technique. Originally, wind tunnel testing would be conducted at pre-specified points in the flight envelope, i.e. M = 0.6, 0.80, 0.9, 0.95, 1.05, 1.1, 1.3. However, at transonic speeds, the aerodynamic coefficients can change substantially and non-linearly for small Mach number increments. The Mach sweep test technique uses a small incremental build up in tunnel Mach number in the transonic range (i.e. M=0.02). As may be seen in Figure 3, the yawing moment for the GBU-32 store changes by more than 100% between M = 0.90 and 0.92. Furthermore, aircraft configuration changes have a significant impact on the store aerodynamics. The large yawing moment effect of the Targeting Forward Looking Infrared (TFLIR) can be easily seen in Figure 3.

F-18C/GBU-32 Mach Sweep

Figure 3

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Another advantage of the Mach sweep technique is that it is easy to identify the critical Mach numbers for the remainder of the test. For the GBU-32 and GBU-38, most of the grid data were taken only at M = 0.85 and 0.95; an excellent match with the flight test data were achieved[6].

3.0 FLIGHT TESTING

Two developments in flight testing have considerably improved the efficiency of the integrated store separation process. These were the development of high quality acceleration and angular rate telemetry data, and testing from both sides of the aircraft in a single flight. Telemetry data enabled a continuous improvement in the M&S process and real-time decision making, while testing from both sides of the aircraft enabled twice the number of tests to be conducted for a given flight.

As may be seen in Figure 4, the original pitch, yaw and roll predictions for the GBU-38 separating from a Canted Vertical Ejector Rack (CVER) were in poor agreement with the test data, as computed via the Navy Generalized Separation Package (NAVSEP). When the trajectory code was modified to take into account the rack vibration effect evident from the telemetry data, the predictions[6] were considerably improved using the modified NAVSEP code (NAVMOD).


Figure 4
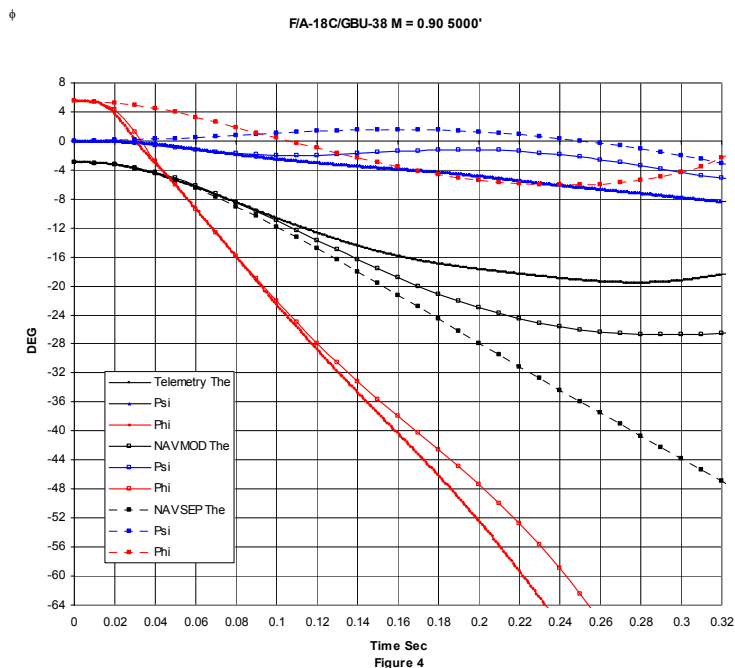
4.0 CFD

Over the past fifteen years, the US Air Force and Navy have made an effort to validate and accelerate the insertion of CFD methods into the store certification process. There have been several organized international conferences for this purpose.

4.1 Wing Pylon Store CFD Challenge

The first of these was for the Wing/Pylon/Finned-Store, which occurred in Hilton Head, SC in the summer of 1992. One of the important results from this initial conference was the discovery that full potential methods[7]

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gave answers equivalent to those provided by an Euler[8] code for the wing lower surface in the presence of the store, Figure 5.

Wing Lower Surface
M = 0.95

Figure 5
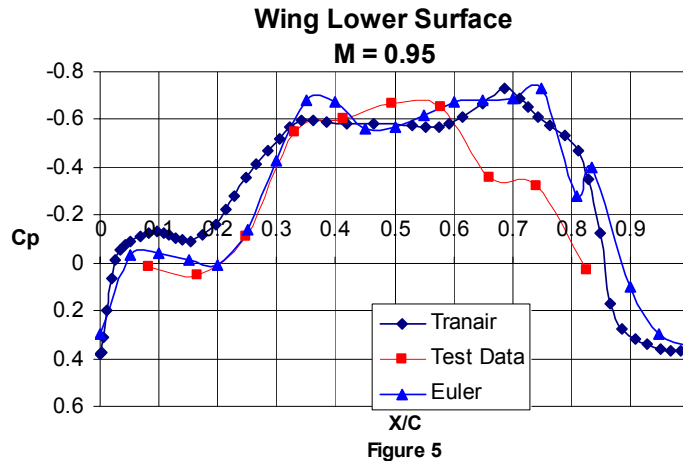
4.2 F-16/Generic Store CFD Challenge

The second conference was sponsored by the Office of the Secretary of Defense (OSD) funded Applied Computational Fluid Dynamics (ACFD) program. This was for the F-16/Generic Finned Store; the conference took place in New Orleans in the summer of 1996 (ACFD Challenge I). For this meeting lower order [9] solutions again exhibited good agreement with Euler and Navier Stokes codes.

4.3 F/A-18C/GBU-31 CFD Challenge

The last ACFD sponsored conference was the F-18/Joint Direct Attack Munition (JDAM) CFD Challenge (ACFD Challenge II). Large sets of wind tunnel and flight test data existed for the F/A-18C JDAM configuration, Figure 6, and all the participants showed excellent correlation with both the wind tunnel and flight test results. A detailed summary of the results for ACFD Challenge II is available[10].
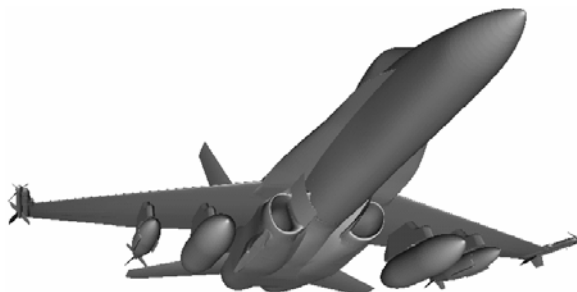

Figure 6

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4.4 F/A-18C/MK-83 PSP CFD Challenge

The last CFD Challenge was conducted under the auspices of The Technical Cooperative Program (TTCP) Key Technical area (KTa) 2-18 for the F-18C/MK-83 store, Figure 7. Comparisons were made with Pressure Sensitive Paint (PSP) data as well as flight test store trajectories. As may be seen in Figure 8, all the participants demonstrated good comparisons with the store lower surface pressures. The best comparisons were obtained using the FLUENT code run in a viscous mode (UK).

Figure 7

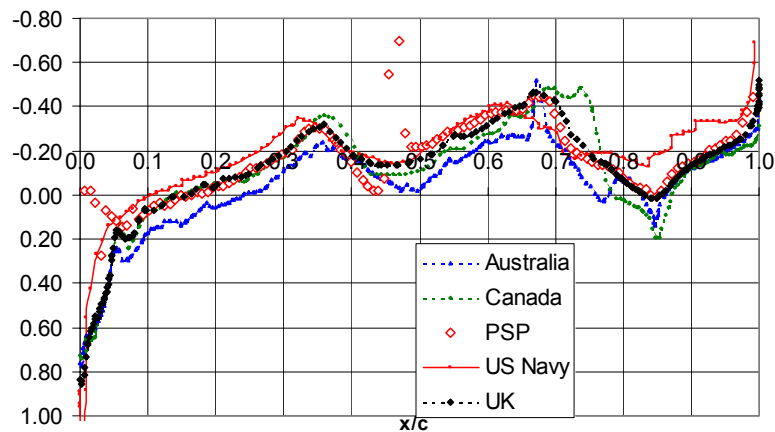**F-18/MK-83 BL 143 store C_P M = 0.90 α = 4.5**

Figure 8

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The Navy often uses[11] CFD to reduce or replace the amount of wind tunnel testing.

5.0 FUTURE CHALLENGES

It appears that aircraft external store testing has reached a mature phase. Lockheed has recently demonstrated[12] that CFD can be used to design an aircraft to be "store friendly', and that the aircraft performance is actually improved by the process.

The next generation of strike aircraft is expected to employ munitions from internal bays under subsonic, transonic and supersonic flight conditions. Current simulations for such weapon separations are immature and have not yet been validated. A lack of flight test data, combined with the inherent difficulties of modeling separation from aircraft cavities in the wind tunnel, have slowed the development of simulation codes necessary to predict weapon trajectories from internal weapon bays. The absence of validated trajectory simulation codes will increase the risk and cost of store certification efforts for aircraft such as the F-22, F-35 Joint Strike Fighter (JSF) and Unmanned Combat Air Vehicles (UCAV).

5.1 F-111/Small Smart Bomb (SSB)

The separation of a Small Smart Bomb (SSB) shape from the Royal Australian Air Force (RAAF) F-111G weapons bay provided the data necessary to validate computational trajectory simulations codes. By providing this data early in the development cycle of both miniature munitions and the aforementioned aircraft, the computational models can be matured and validated to support certification efforts.

A total of 16 weapons were released in 8 different sorties. Weapons were released at a variety of Mach numbers and altitudes starting at 0.8, 20K – 1.3, 30K respectively, with and without the Active Separation Control (ASC) device. Acoustic and camera data were taken prior to release of the SSB and continued until after separation of the last weapon.

Unfortunately, for the F-111/SmallSmart Bomb, neither the wind tunnel nor CFD came close to matching the flight test results. The reason that the wind tunnel did so poorly was due to the aft store trajectories starting some two feet (full scale) from the carriage position. The forward store was tested at the end of stroke position and, although those trajectories seemed to compare better, sting interference effects in the cavity might have corrupted the subsonic and transonic results.

Wind tunnel testing and analysis were performed by Air Force Research Lab (AFRL), Air Force Seek Eagle Office (AFSEO) and AEDC. The flight test program was developed and executed by the AFRL and RAAF.

5.2 Wind Tunnel Data Analysis, Arnold Engineering Development Center (AEDC)

There were several systematic discrepancies between flight test and wind tunnel results[13]. The flight tests showed a tendency for the store to roll clockwise (looking from the rear), move laterally inboard, and initially pitch nose-up from the forward station and nose-down from the aft station relative to the wind tunnel predictions. The tendencies were consistent across Mach number and, therefore, were thought (by AEDC) not to be the result of aerodynamic differences. It was believed that these differences were because of movement of the small multiple ejector rack (SMER) during store launch, thus inducing non-vertical forces to the store.

The movement of the SMER has two parts. First, the SMER is flexible and large moments must pass through the structure to reach the lugs and be transmitted to the aircraft pylon. Initial pitch rates were thought to be the

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result of the SMER flexing up, relative to its c.g., during release of the front store, thus inducing a nose-up pitch, and the same for rear store, inducing a nose-down pitch.

Note that RAAF officials don't necessarily believe13 that this was the case. They reply, "…However, it can be seen in figures 14 and 15 of appendix A13 that during supersonic flight test with the ASC off, the pitch rates of the store were very similar to that obtained from wind tunnel testing. Hence it is Aircraft Research and Development Unit's (ARDU) opinion that the pitch anomaly during flight test was not due to the flexing of the (SMER), as the anomaly would have been observed consistently across Mach number."

5.3 Wind Tunnel Data Analysis, Naval Air Systems Command (NAVAIR)

An independent attempt was made to determine the causes for the disagreement between wind tunnel Captive Trajectory System (CTS) predictions and flight test results. Since the ASC blowing simulations might have caused some of this disagreement, only the non-blowing cases were compared.

Reference 13 showed comparisons for the pitch, yaw and roll attitudes. For the subsonic case, both the front and rear stores trajectory predictions indicated opposite trends to the pitch test data, with the rear trajectory showing a much larger discrepancy than the forward store. For the transonic and supersonic cases, the pitch attitudes were in reasonably good agreement for the forward store, but not for the aft store.

At the subsonic and transonic Mach numbers the yaw trends were reasonably well predicted.   Such was not true for the M = 1.3 case.   In this case the front store prediction matched the flight test trends, but the rear store showed the opposite effect.

The front and rear store exhibited substantially different roll behavior for all three Mach numbers. Since the flight test roll magnitude was essentially the same for all three Mach numbers, this might be caused by rack rolling effects during the ejector stroke.   This type of behavior was observed in the recently completed F-18C/GBU-38 flight test program[6], and can be readily compensated for. The flight test trajectory displacement in y consistently exhibited similar trends. It appears that the discrepancy in y and roll can be attributed to inertial effects.

However, the trends in pitch and yaw can't be attributed to inertial effects, since there is no similarity with Mach number (the ejector force effects seen in Reference 6 were consistent throughout the Mach number range for pitch, yaw and roll). It is much more likely to be due to the wind tunnel testing methodology. As can be seen in Figure 9, the SSB is attached to the CTS system by a bent sting. When this sting is inserted in the forward bay location, the aft part of the sting will be close to the aft wall. At subsonic and transonic speeds, the interaction between the sting and the cavity flowfield in the aft region can cause large changes in the flowfield around the store. At supersonic Mach numbers, the flowfield effects might not be as significant, since they won't propagate upstream.
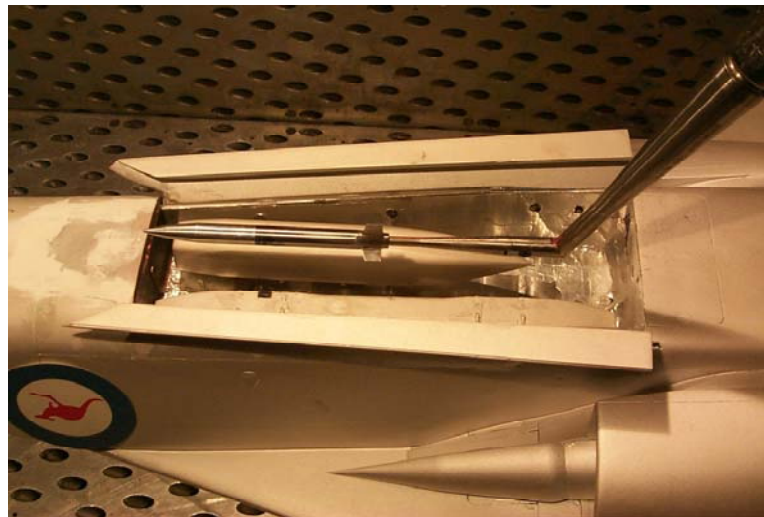
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Figure 9

The discrepancy for the aft store is readily accounted for, since the aft trajectories were initiated four body diameters from the carriage position. As may be seen in Figure 10, the pitching and yawing moments seen[14] by a MK-82 store in the aft part of a cavity during the Navy Internal Carriage and Separation (NICS) test at three different store pitch attitudes (α = -10, 0, 10) vary by an order of magnitude when the store passes through the shear layer (Z/D=1). The behavior seen in the SSB flight test data can be explained by referring to the pitching moment variation in Figure 11, where the solid symbols represent the SSB and the open symbols represent the MK-82. The MK-82 pitching moment changes sign as the store leaves the cavity. It's negative inside the cavity, and positive outside. If the trajectory had been initiated outside the cavity, the store would have a strong tendency to pitch nose up; inside the cavity, the tendency would be to pitch down. That is exactly the behavior seen for the small smart bomb.
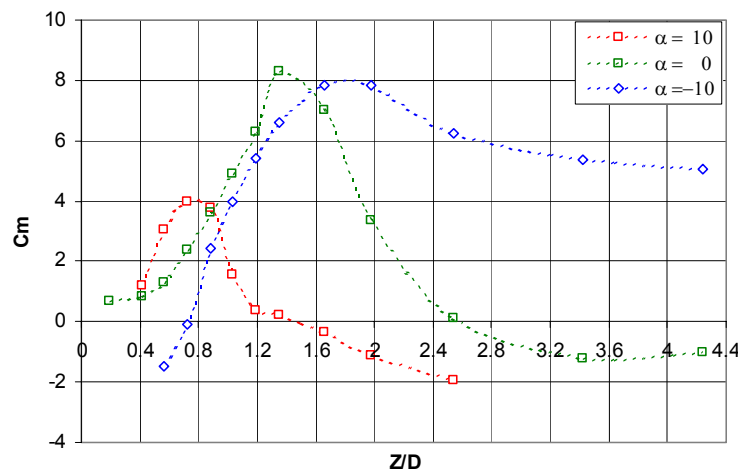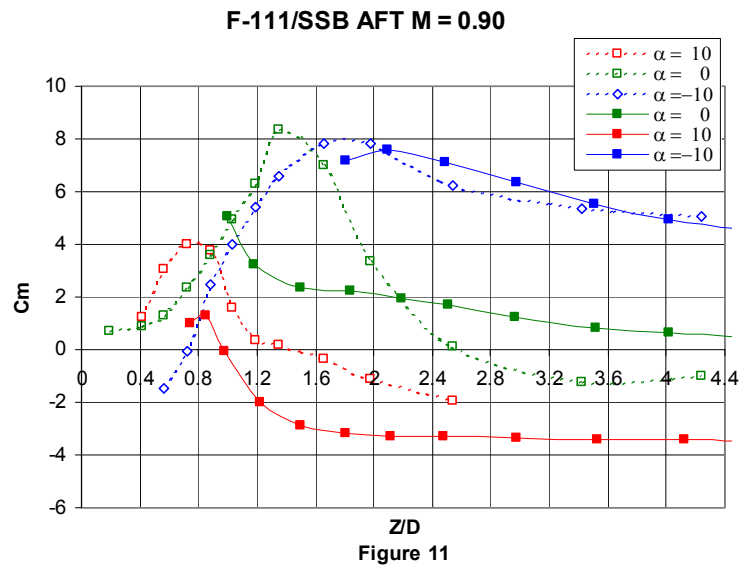
NICS MK-82 M = 0.85

Figure 10

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F-111/SSB AFT M = 0.90

Figure 11

6.0 CONCLUSIONS AND RECOMMENDATIONS

During the past twenty years the Navy has successfully used three tools to provide an airworthiness certification for new aircraft and stores. These were: Wind Tunnel Testing, Computational Fluid Dynamics (CFD) analyses and Flight Testing. There have been considerable advances in all three areas. It now appears that external store testing has reached a mature phase. Although challenges still exist in releasing stores at high Mach numbers, the process is well understood. As may be seen in Figure 12, recent aircraft may well have considered store integration as a design parameter, since the fuel tanks appeared to be area-ruled.

Figure 12

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The next generation of strike aircraft is expected to employ miniature munitions from internal bays under subsonic and supersonic flight conditions. Current simulations for such weapon separations are immature and have not been validated. A lack of flight test data, combined with the inherent difficulties of modeling miniature munitions in the wind tunnel, have slowed the development of robust simulation codes necessary to predict weapon trajectories from internal weapon bays. The absence of validated trajectory simulation codes will increase the risk and cost of store certification efforts for aircraft such as the F-22, Joint Strike Fighter (JSF) and Unmanned Combat Air Vehicles (UCAV). The separation of a Small Smart Bomb (SSB) shape from the Royal Australian Air Force (RAAF) F-111G weapons bay demonstrated that trajectory simulations codes for weapons released from bays are inadequate.

Both wind tunnel and CFD based simulations failed to predict the flight test trajectories. The proper turbulence model for cavity flowfield predictions has yet to be determined. Perhaps Large Eddy Simulation (LES) must be used. The wind tunnel data suffers from geometric constraints. Stores mounted with an aft sting can't be properly positioned inside the cavity; if a bent sting is used, as was the case for the F-111/SSB, for the aft bay position the trajectory had to be initiated outside the bay. Since the store aerodynamic coefficients can vary by an order of magnitude passing through the shear layer, these types of trajectory simulations are useless.

Since wind tunnel based simulations are subject to experimental error, and the CFD predictions failed to match the flight test data, using the two techniques independent of each other has obvious limitations. However, a combination of the two might be the optimal approach. The wind tunnel can be used to collect the aerodynamic data – if the store were mounted on a strut sting, grid and CTS data could be obtained inside the cavity. CFD could then be used to determine what the incremental interference effects were. It has long been recognized that CFD is better at providing incremental effects than total coefficients. Applying CFD and wind tunnel in an integrated approach should give the best possible answer.

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DISCUSSION EDITING

Paper No. 24: **Studies Advances in Modeling and Simulation Capabilities for Predicting Store
Trajectories – Past Success and Future Challenges**

Authors: Alex Cenko, Al Piranian

Speaker: Alex Cenko

Discussor: Malcolm Tutty

Question: You made a statement that although the predicted aerodynamics did not agree with experiment, the trajectory did. I believe that this is due to the body being heavy and the aeroforces are small compared to the inertial ones. Ballistic parameters such as W/qS need to be evaluated in this connection. ($W/qS \gg 1$)

Speaker's Reply: I totally disagree. Discussion of this experience…. Etc. etc.

Discussor's Reply: $qS/W \to 0$; How would Author's disagreement relate to that limit.

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